VNA for 5 – 30GHz (Part 1)

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Introduction

This two-part article describes the hardware of a home built Vector Network Analyzer (VNA) for the measurement of transmission and reflection in the area of 5 – 30 GHz. The system is built in modules, so it is also possible to cover other frequency bands with this same approach. The design is based on the well known 0 – 60MHz VNA of Paul Kiciak, N2PK (see references). To control the functions of this VNA the excellent software 'myVNA' from Dave Roberts, G8KBB is used.

What is a Network Analyzer used for?

A Network Analyzer in the microwave band allows the measurement of the S-parameters of a 2- or 4-pole device. This can be, for example, the gain of an amplifier, the reflection coefficient of an antenna or the complex input impedance of a FET. Beside a power meter and a spectrum analyzer, a network analyzer is therefore one of the most important professional instruments for the development of microwave circuits. Unfortunately, such systems are very expensive (in particular for frequencies above approx. 3GHz). Even if purchased in a used state, they are often unaffordable for amateurs. The do-it-yourself construction of such a system seems also to be very difficult because the wide bandwidth is very difficult to achieve with conventional components. However, some new MMICs have become available which make the design of broadband amplifiers and mixers possible. Another point is that with today's available computing power, errors such as nonlinearity and gain variations in the RF systems can be largely compensated by a calibration process. This approach greatly improves the accuracy and is heavily used by manufacturers of professional network analyzers.

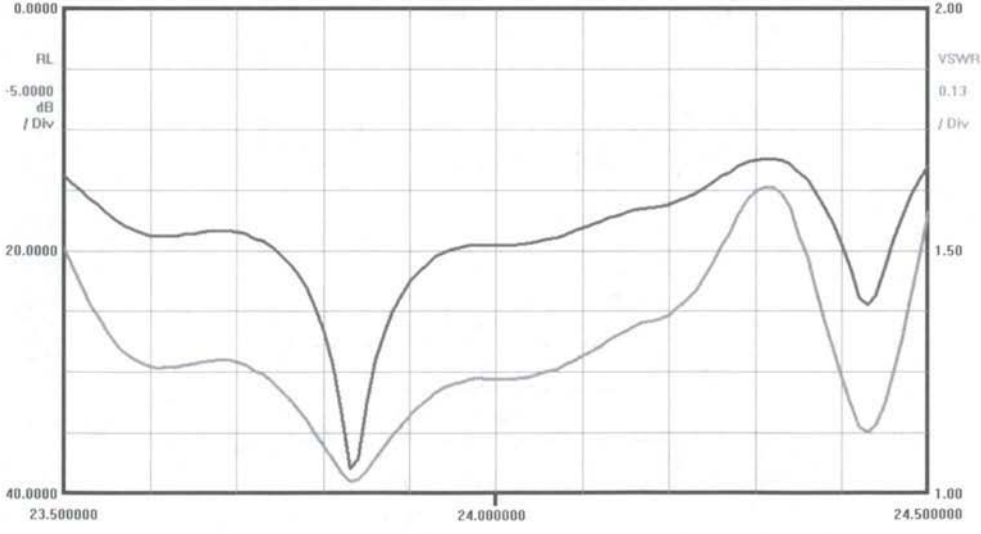


Figure 1: The S11 reflection of a 23.85 GHz patch antenna measured with the presented system. The return loss (S11, dark curve, left scale) shows a minimum value of –38dB at a frequency of 23.83GHz which corresponds to a VSWR value of approx. 1:1.03 (lighter curve, right scale)

Scalar vs. Vector Network Analyzers

The available network analyzers on the market can be divided into two major categories: Scalar Network Analyzers (SNAs) and Vector Network Analyzers (VNAs).

A scalar system consists of a signal source which generates a frequency sweep in the desired range. For measuring transmission parameters (S21) this signal is fed to the device under test (DUT, e.g. an amplifier). The output of the DUT is measured with a detector and plotted against the frequency. If we need to measure the return loss (S11) instead, the signal from the source is fed first to a directional coupler before it reaches the DUT. The output from the directional coupler again is measured by a detector and plotted against the frequency.
The disadvantage of such a scalar system is that it does not provide phase information, which makes the results much less useful. For example, the design of a compensation network e.g. for FETs is not possible with such limited information, Other disadvantages of scalar analyzers include the restricted dynamic range of the detectors and the limited directivity of the coupler. Error correction is not possible (except a so-called Response Calibration), once again because the lack of phase information.

In a Vector Network Analyzer (see Figure 2) a small part of the signal from the RF source is directly fed to the 'Incident' input channel of the receiver/detector. This will be the reference signal which is used for the computation of results. The rest of the signal from the RF source is fed through a directional coupler into the DUT. The reflected output from the directional coupler goes to the 2nd input channel of the receiver ('Reflected'). The output signal from the DUT is routed to the 3rd channel of the receiver ('Transmitted'). In contrast to a scalar system these three channels are all down-converted to a common intermediate frequency by the use of mixers or samplers. The three IF channels still contain the amplitude- and phase-information of the respective RF signals. The three IF signals are now sampled and the amplitude and phase of the 'Reflected' and 'Transmitted' signals are both calculated, relative to the reference signal ('Incident'). The Incident and Reflected channels provide information to calculate the S11 parameters of the DUT, while the Incident and Transmitted channels provide S21. The presentation on the display can now take place in a cartesian manner (identical to the scalar system) or also in a polar manner including phase information (Smith chart). Other advantages of this system are the bigger dynamic range of the receivers and the possibility of an error correction. Further information can be found in the H-P Application Note 1287 (see references).

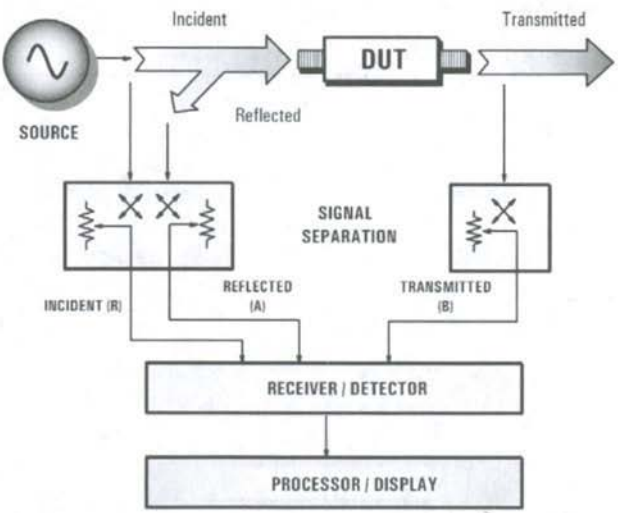


Figure 2: Architecture of a Vector Network Analyzer

Analysis of different circuit concepts

For the do-it-yourself construction of a VNA we have to deal with 4 basic blocks which exist in every VNA system (sometimes constructed as physically separate units, e.g. in the well known 8510 from H-P).

1. Signal Source

The signal stimulus source must be able to deliver a RF signal with adjustable frequency and a reasonably constant power level. For systems in the frequency range below 500MHz a DDS can be used (e.g. the 0–60MHz VNA by N2PK). More broadband systems extending to higher frequencies often use a YIG oscillator (e.g. 8341 from H-P). Another possibility is the use of a PLL (see also DUBUS 2/2009). Phase noise is an issue if the IF signal is generated by two independent RF sources or if we want to measure a very narrowband DUT with a high Q factor. In our concept we use a PLL oscillator whose frequency range is extended by additional multipliers and dividers.

2. RF Part

The RF part feeds the output of the signal source via a directional coupler to the test port. The Incident (reference) signal, the Reflected signal from the DUT input and the Transmitted signal from the DUT output (see Figure 2) are each fed to their own individual down-converting mixer. To generate an intermediate frequency we need a local oscillator (LO) signal that has a constant frequency offset relative to the signal source. This LO signal could either be generated by a second microwave oscillator (expensive, problems with phase noise) or it can be generated by SSB modulation of the existing signal source. H-P go another way in their 8510-line of VNAs: they create the frequency offset by a second PLL-loop on the IF signal and samplers for the down-conversion. However, also this implementation is too complex for a do-it-yourself construction.

The approach of N2PK in his 0–60MHz VNA is to use a Zero-IF receiver (also known as 'Direct Conversion'). Instead of measuring the phase and amplitude of an IF signal, we work with DC voltages. The mixers down-convert their respective input signals using an LO at the same frequency as the RF stimulus signal (a second identical DDS, in fact). The output from each mixer is therefore a DC signal. To measure phase information, the N2PK concept changes the phase of the LO signal by reprogramming its DDS, while leaving the RF stimulus DDS at the reference phase of 0°. With the use of this LO phase shift we can sample several well-defined points on an IF signal. As a general rule the IF signal is sampled in 4 sequential measurements at 4 different LO phases (0°, 90°, 180° and 270° relative to the reference, the RF stimulus signal which remains at 0°). We then get a sequence of 4 different DC output voltages U_1 to U_4 corresponding to steps in phase-difference of a quarter period (these sampling points have a random starting offset: LO-phase 0° is not corresponding to IF-phase 0°!). The amplitude of the 'true' IF signal can be determined from:

$$\hat{U}_{ZF} = \frac{1}{2}\sqrt{(U_1 - U_3)^2 + (U_2 - U_4)^2} \qquad (1)$$

The phase is calculated relative to sampling point #1, from:

$$\varphi_{HF} = \arctan\frac{U_1 - U_3}{U_2 - U_4} \qquad (2)$$

Further information about this procedure can be found in the documentation of the N2PK Vector network Analyzer (see references).

3. IF Part

If the Zero-IF approach was not chosen (here the amplitude- and phase-information was already calculated), the 3 signal channels would have to be further analyzed at the IF. We first have to calculate the amplitude difference from 'Reflected' to 'Incident' and from 'Transmitted' to 'Incident'. Then the same has to be done for the phase. For this measurement we can use an integrated Gain/Phase Detector like the AD8302 from Analog Devices. The disadvantage of this solution is the limited phase range as well as the fact that the amplitude difference is already converted into dB (which we don't want). An additional error correction is nearly impossible therefore. The measurement can also be realized in a traditional manner with analog multipliers.

Because we chose the Zero-IF approach in our case, we must merely ensure that the IF signal (which in fact is a DC signal) is converted with an A/D-converter with a high dynamic range. For this application we need precision DC amplifiers and at least 16Bit of A/D resolution!

4. Display

Now the measured signals have to be error corrected (see next section) and displayed in a suitable form. Professional systems use for this purpose an integrated computer system with monitor. For the amateur application the use of a PC for this purpose makes more sense. In this case we have to make sure that the measured values are transferred to the PC via a suitable connection (e.g. USB). Then the calculation and visualisation of the data can follow there. For this purpose there already exist some excellent software written by radio-amateurs (e.g. 'Exeter' from W8WWV or 'myVNA' from G8KBB). The system introduced here co-operates with the myVNA software. Figure 3 shows a screenshot of this application. An exact description of the capabilities of this software can be found in the references.

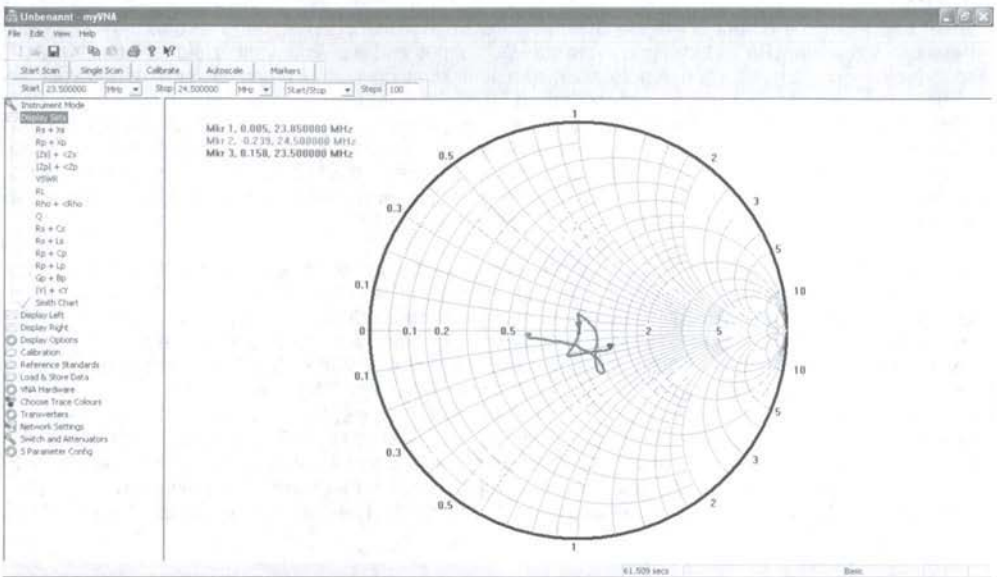


Figure 3: Screenshot of the application 'myVNA' from G8KBB, which is used to control the hardware of the Microwave Vector Network Analyzer described in this article. For this Picture the same 23.85GHz patch antenna as in Figure 1 was used.

Error correction

Our constructed hardware will never become 'perfect', there will always be several sources of systematic errors. The aim of the error correction is to compensate these errors. Today this technology is used with all professional VNAs. Only by means of this error correction can the high dynamic range and precision of modern VNAs be achieved. An error correction implemented by software is often less expensive compared to highly linear hardware, but unfortunately this means that modern VNAs do not necessarily have 'better' RF hardware than older machines.

The systematic errors appearing in a VNA (a possible temperature drift or noise are not systematic errors!) can be divided into 6 categories, as follows. All of them can be corrected by calibration.

1. Reflection Tracking

This corresponds to an error in the frequency response of the reflected signal. This error could be created e.g. by a frequency dependence in the S11 mixer or the directional coupler.

2. Directivity

The directional coupler for measuring the return loss ideally delivers only a small portion of the reflected signal from the DUT, but not a signal directly coupled from the signal source. Because the isolation from this port is limited, we get this additional error. Figure 4 shows this as an unwanted signal from the Reference (R) port to the Reflected (A) port.

3. Source Match
The VNA test port which delivers the source signal to the DUT should have a source impedance of exactly 50Ω. Even a small deviation leads to a reflected signal from the DUT, even if the DUT has a perfectly matched 50Ω impedance. This error occurs e.g. by a not perfectly matched output-stage inside the VNA.

4. Load Match
The output of the DUT is connected to the input port of the VNA (port B in Figure 4). If the input impedance of this VNA port is not precisely 50Ω, a DUT with an accurate 50Ω output impedance will not transfer the full power to the VNA. This error is created e.g. by a mismatch of the input mixer.

5. Transmission Tracking
This error describes a divergence of the ideal frequency response of the VNA input port. An ideal connection between VNA output (signal source) and VNA input must have a loss of 0dB and a phase angle of 0° over the full frequency range. This error is generated e.g. in the input mixer, in the signal source and in the unavoidable use of connecting cables to the DUT.

6. Crosstalk
Because of crosstalk within the VNA, the input port B also 'sees' a direct leakage signal which has not passed through the DUT. This crosstalk can e.g. occur from the signal source directly to the input mixer.

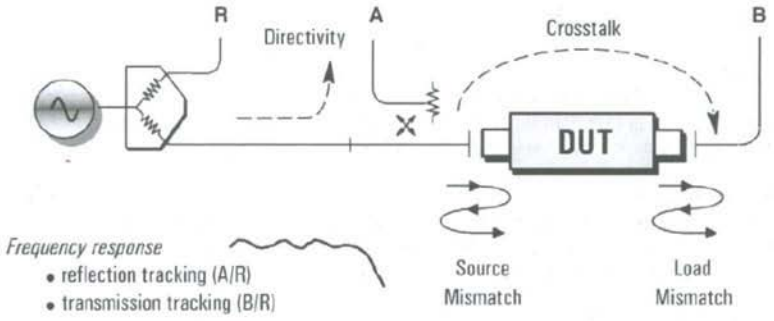


Figure 4: The systematic errors appearing in a VNA can be divided in 6 groups. All of them can be eliminated by a calibration.

All these 6 errors can be calculated with a so-called SOLT-Calibration and can also be eliminated by subtracting the calculated errors from the measured signal. For the determination of these error terms a calibration is carried out before the real measurement. For this calibration we have to connect consecutively 4 'perfect' (or at least well known) reference terminations to the VNA ports. These references are:

- **S**hort, typically an SMA connector with a perfect short circuit inside
- **O**pen, typically an SMA-connector with an open end (non radiating, but including fringing capacitance)
- **L**oad, a perfect 50Ω termination
- **T**hrough, a direct connection between the two test ports of the VNA

This SOLT-Calibration is a so-called 6-Term error correction which is carried out with instructions given by the software. (A 12-Term error correction would be necessary if both test ports of the VNA are interchangeable, what means that both ports are able to source a signal to the DUT. In the system presented here, this is not possible because of complexity and therefore a 6-Term correction is used.) However, this error correction also shows that the accuracy of the measurements results relies heavily on the accuracy of these 4 SOLT references. In a professional system these references are combined in a 'Calibration Kit' which is handled very carefully and has calibration traceable to international standards.

For our system we need therefore either such a Calibration Kit or at least measured and well known (though not 'perfect') standards; of which more later (next part).

Requirements for our system

After the theoretical part describing how a VNA system can be built up, we now should set out the requirements for the system to be realized:

- Measurement of reflection (S11) and transmission (S21). We decide not to make an automatic reverse measurement of the DUT because this will increase the complexity of our system. To measure the reverse parameters (S12 and S22) we have to turn the DUT.
- Wide frequency range, at least the 10GHz and 24GHz amateur bands should be covered
- The power level of the RF source should be adjustable in some steps
- The frequency of the RF source should be stabilized by a crystal, so that narrowband DUTs could be measured
- Usable dynamic range should be >40dB (S11) and >70dB (S21)
- Zero-IF architecture
- Error Correction
- Use of already existing PC software for hardware controls
- PC connection via a widely used connection (also on notebooks), e.g. USB
- It should be possible to apply an additional DC-bias on both test ports. This enables measurements of components that require some bias for working (e.g. FETs)
- Scaleable modular system, so that other frequency bands could also be covered.

The realized system consists of 3 PCB boards:

1. Microwave part

This board takes the signal from the synthesizer and feeds it via a microstrip directional coupler to the testport. The coupled signal is downconverted by a mixer and is available as an analogue DC-voltage on a connector. The same happens with the signal coming from the second testport.

2. CPU and Power Supply

This PCB contains the power supply (switched and linear regulators) for the microwave part and also for the synthesizer. The A/D-converters and the CPU, which controls the instrument and communicates with the PC via an USB interface, are also located on this board.

3. Synthesizer

The synthesizer is an extended version of the board described in DUBUS 2/2009. Now a frequency range of 5 – 30GHz is covered. The control of the DDS as well as the PLL is performed by the CPU on the Power Supply board.

By the exchange of single boards it is possible to extend the frequency coverage of this VNA also to lower bands.

Circuit descriptions

1. Microwave part

The completed board is shown in Figure 5 and the schematic in Figure 6. The RF signal from the synthesizer with a frequency range of 5 – 30GHz and an output power of 0 – 10dBm reaches the microwave part by a 2.92mm connector, which is mounted together with a feedthrough in a brass profile with a thickness of 1.5mm on X3 (details for mounting this connector can be found in DUBUS 2/2009). This signal is amplified by U1 (AMMP-5024). This broadband amplifier has a gain of about 14dB in a frequency band of 2 – 40GHz. The operating point of this amplifier is controlled by V_{neg} and VCC4V which both are provided by the Power Supply board. A possible oscillation of this amplifier can be removed by a 100Ω resistor (0402 package) on its input.

The amplified signal is fed to a power divider. The return loss of this device is better than 10dB over the full frequency range. This is more than enough for this application. The left path leads to an I/Q mixer (U4) which we use as a vector modulator. The signals ModI and ModQ (both created by D/A-converters on the CPU board) control the amplitude and phase of the RF signal on pin 8 of U4. The amplitude is in our case

less interesting. We use this mixer to control the phase of our LO-signal. The frequency dependence of this mixer is calibrated once by an automatic calibration-cycle and the values are stored in non-volatile memory. So the CPU has the ability to control the relative phase on the mixer output in 4 steps from 0° - 270°. This signal will later be used as our LO-signal.

The mixer's conversion loss is compensated by the following amplifier U2. Now the generated LO-signal is fed to another power divider, which splits it to both mixers U5 and U6. The input signal from test port X4 is routed to the RF-port of mixer U5. The power applied to this test port should not exceed +10dBm. The connection to 'the rest of the world' is also done by a feedthrough and a 2.92mm connector. X1 can be used to apply a DC-voltage to test port X4. The 'IF' voltage of the mixer (which in fact is a DC voltage) is taken across R7 and is routed differentially to connector JP1. U5 is also an I/Q mixer, but only one of these outputs is used (unfortunately the direct use of both mixer outputs instead of the vector-modulation with U4 does not work sufficiently well).

The return loss measurement via test port X5 is nearly identical to the measurement from test port X4. The reflected signal leaves the directional coupler X6 on port 2, is amplified in U3 by about 14dB and is down-converted with mixer U6. This mixer also uses the phase-shifted LO signal. The IF signal is taken across R10. A DC-bias for this test port can be applied on X2.

The RF signal reaches the directional coupler via U7. This device is a variable broadband attenuator (HMC712 from Hittite). The attenuation range is about 25dB. The output signal is also fed to a detector diode (MA2502 from MA/COM). The DC voltage from this diode can be used for a rough estimation of the output power. The measurement of the voltage is also done on the CPU board. All measured voltages are connected to a 20-pin ribbon cable connector JP1. The power supply for this board (VCC4V and V_{neg}) is also delivered on this connector.

Figure 5 shows the fully assembled PCB. The size is 110x60mm (Eurocard). The board has to be mounted in a metal housing. This housing could be built from brass-profiles with a size of 25x1.5mm. The 3 RF connections are created by feed-throughs which are soldered directly to the microstrip lines. A cut sheet of absorbing foam is glued on the cover of the housing. The connection to the CPU board is implemented by a ribbon cable with a length of about 100mm, threaded through a slit in a sidewall of the housing.

A link to datasheets of all relevant components is found in the references. The directional coupler X6 is implemented as a microstrip structure directly on the PCB. The EM-simulation of the coupler (Figure 7) shows that the coupling coefficient is frequency-dependent and lies at about –13dB (S31). The directivity can be read out as the difference between S41 and S31. For frequencies below 20GHz the directivity is about 15dB and drops to about 10dB for frequencies above 20GHz. The directivity of the whole system is considerably increased by the use of software error correction.

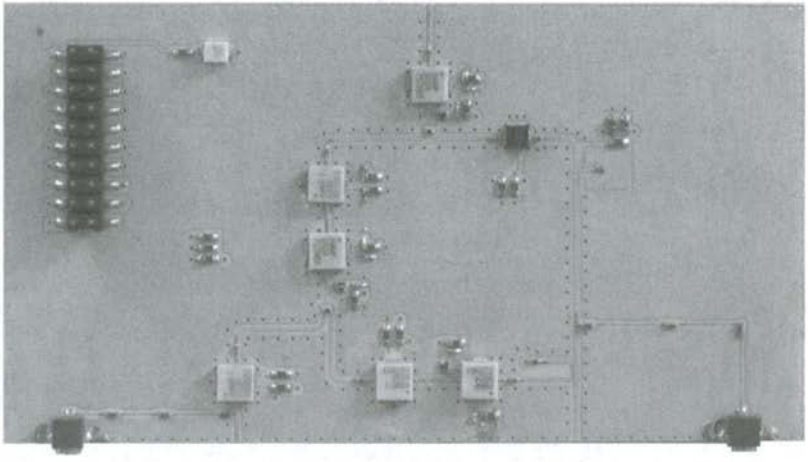


Figure 5: Picture of the assembled Microwave board. The connection to the synthesizer is located on the upper edge. The S11 test port is on the lower right and the S21 test port on the lower left. The small black connectors are for applying DC bias to the RF test ports.

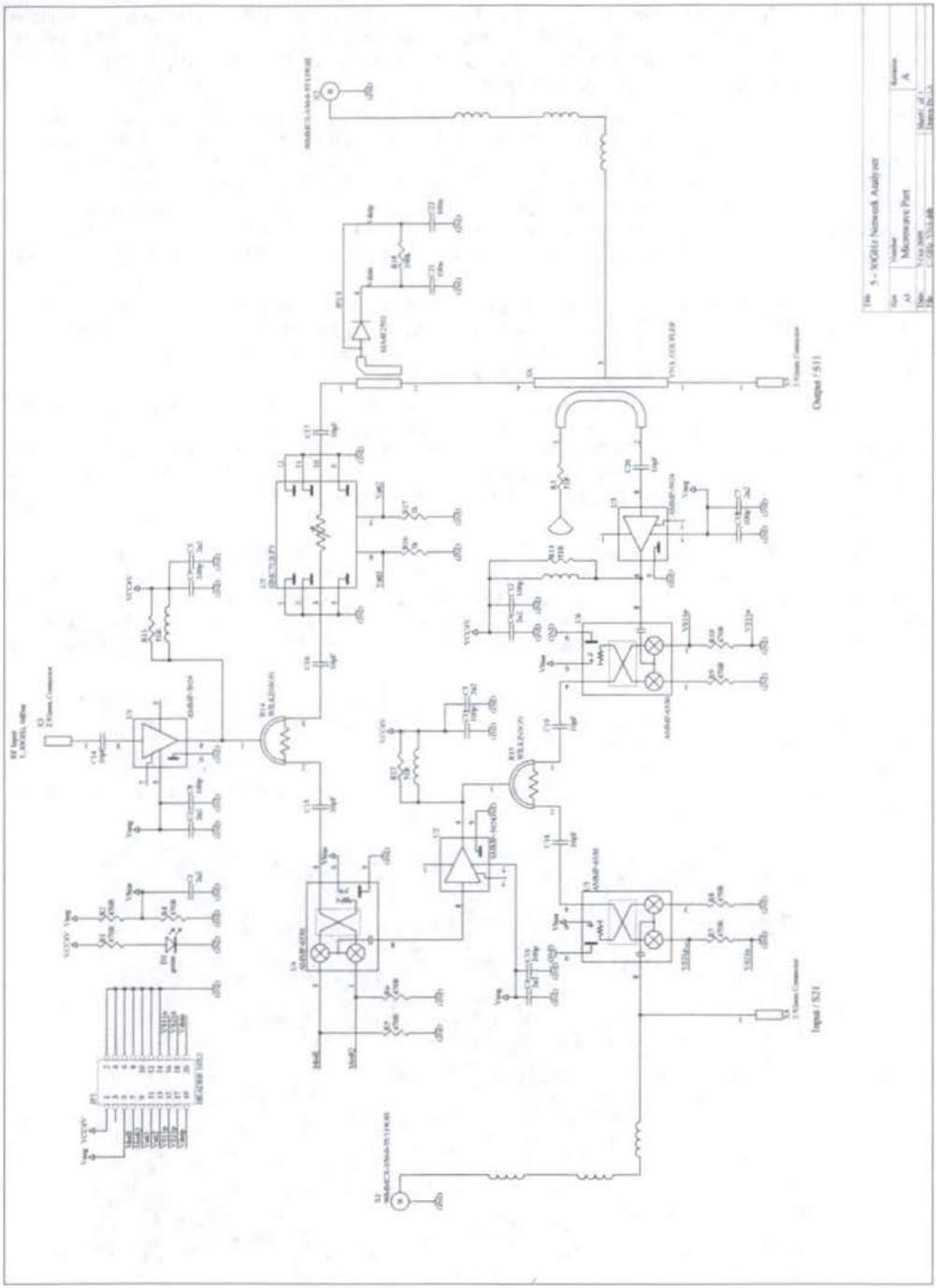


Figure 6: Schematic of the Microwave board.
By the use of MMICs the circuit remains very compact.

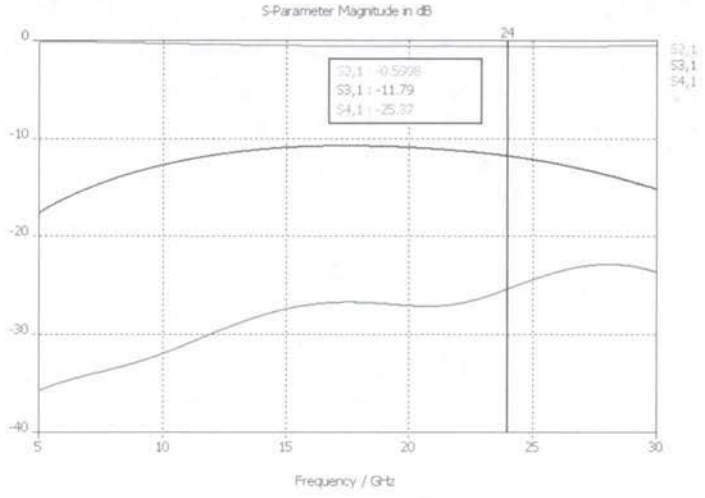


Figure 7: Simulation of the directional coupler. The coupler is kept very simple and its clearly visible frequency dependence is 'leveled' by the error correction. The directivity of the coupler itself averages about 15dB.

2. CPU and Power Supply

The circuit diagram of the CPU board with its 6 pages has become rather extensive, so it is pictured strongly reduced in this article. However, it can be downloaded as a PDF file (see references). On this board, Figure 8A, we find 2 connectors (20-pole double row headers) for the Microwave board and the Synthesizer board, a USB-connector for the PC and a connector for the 12 – 24V DC power supply.

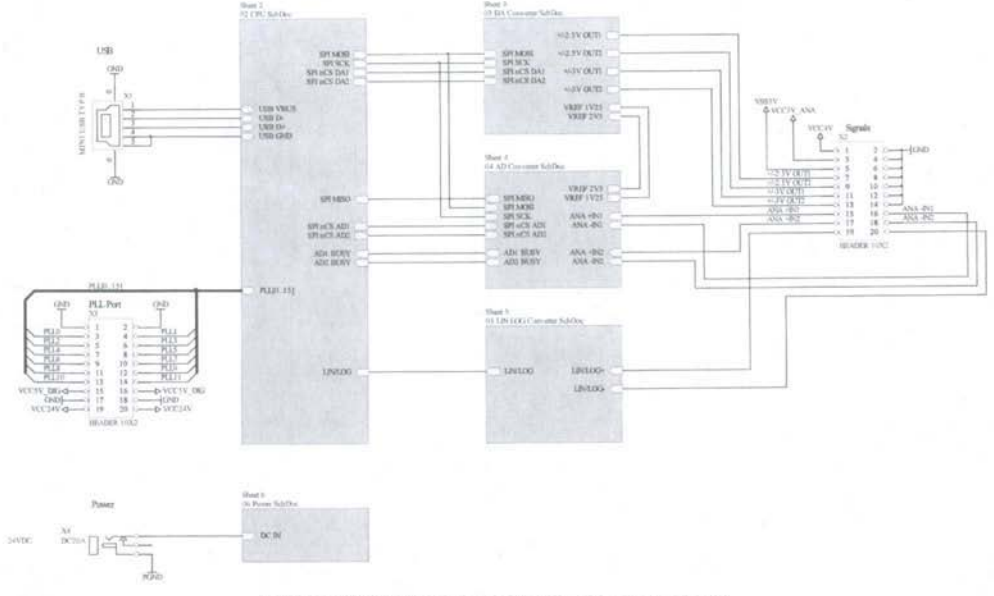


Figure 8A: Schematic of the CPU part (page 1)

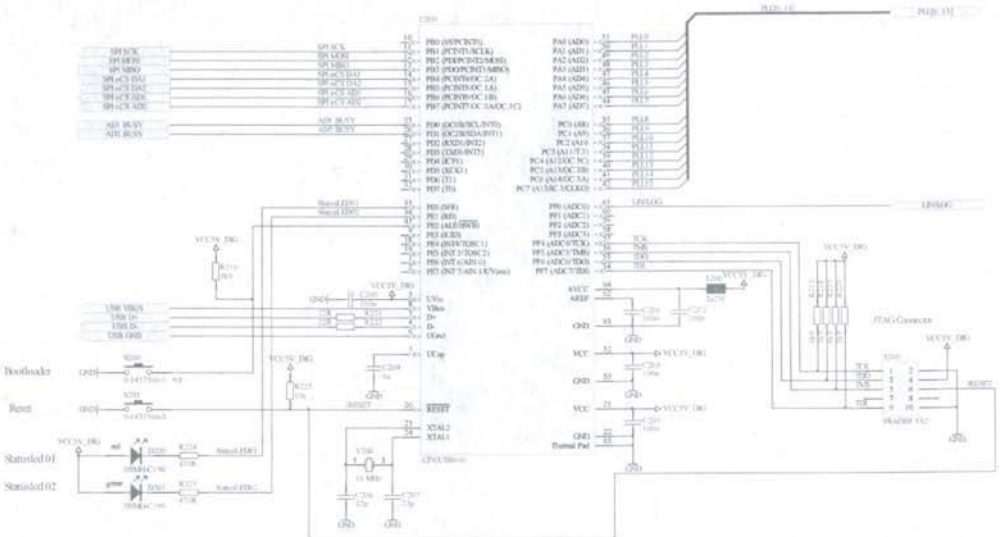


Figure 8B: Schematic of the CPU part (page 2)

The CPU itself is an Atmel AT90USB646 chip (Figure 8B). Port B and port D (left side) are used to control the A/D- and D/A-converters for the Microwave part. The 16 lines of port A and port C (right side) control the DDS and PLL of the Synthesizer PCB. The standardized X200 interface is used for programming the processor. Here Atmel's programming tools as JTAGICE can be connected. 2 LEDs show the current state of the CPU.

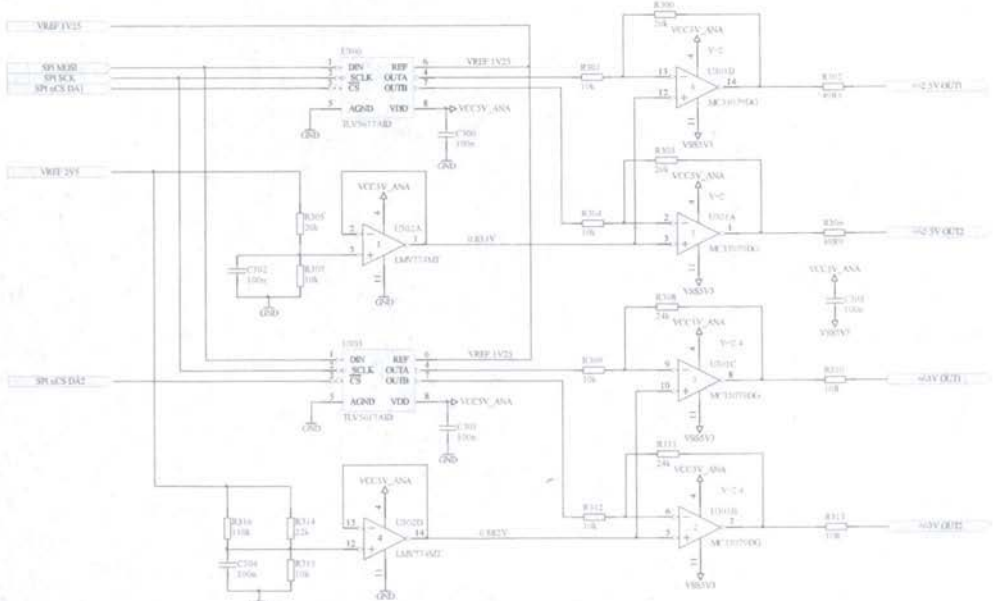


Figure 8C: Schematic of the CPU part (page 3)

The D/A-converter U300 on page 3 (figure 8C) is used for the generation of the I/Q signals for the vector modulator (phase control of LO signal). The amplifiers U301A and U301D set the output voltage to +/- 2.5V. These signals are fed via the 20-pin connector to the Microwave board. The lower D/A-converter (U303) creates the control voltages for the variable attenuator.

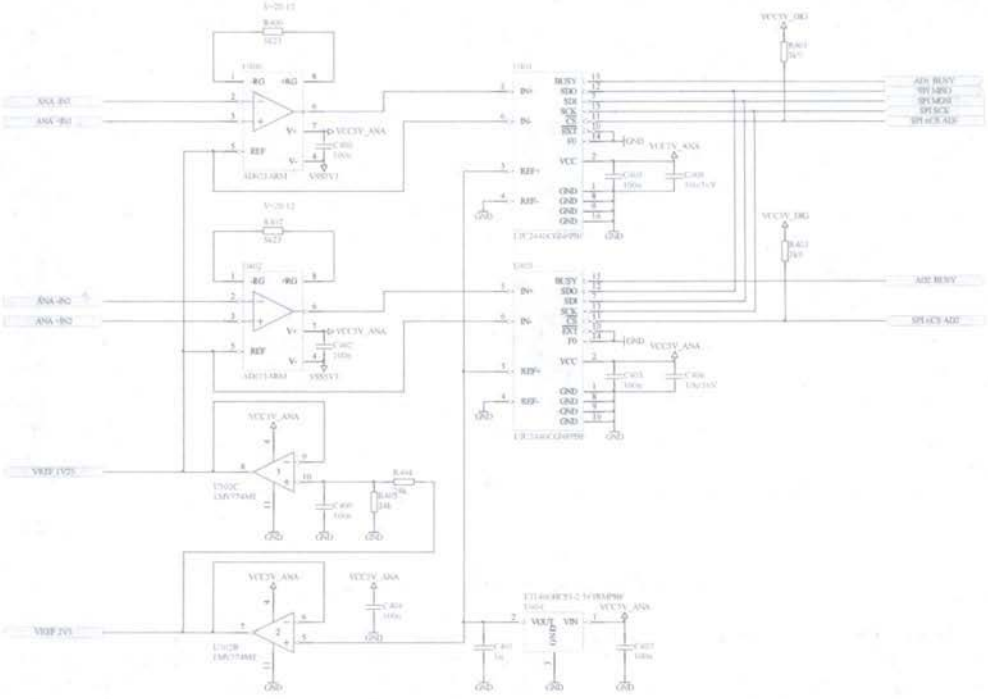


Figure 8D: Schematic of the CPU part (page 4)

On page 4 the signal-processing of the mixer signals takes place. The differential output signals from both mixers are amplified by a precision instrumentation amplifier (U400/U402, AD623 from Analog Devices) before these signals are sampled by 24Bit A/D-converters (LTC2440 from Linear Technology). The huge dynamic range is necessary for accurate software error correction. The effectively used dynamic range is about 19 Bits. The reference voltage of 2.5V is delivered by a precision voltage reference (U404). The digital values are read out from the CPU by a SPI protocol (Figure 8D).

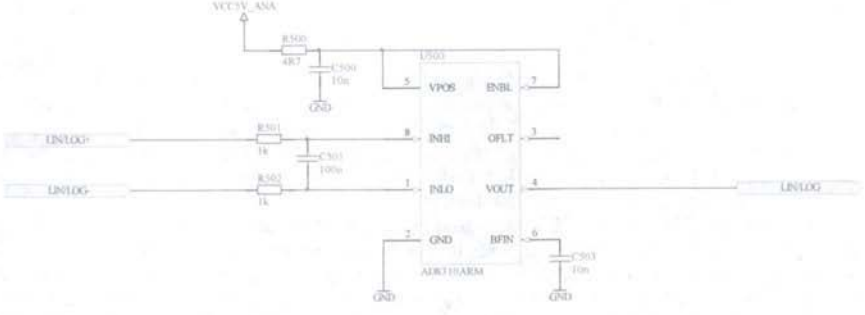


Figure 8E: Schematic of the CPU part (page 5)

Page 5 (Figure 8E) contains only a Lin/Log converter. This chip takes the rectified RF voltage (output power after RF attenuator) from the detector diode and converts it to its logarithmic representation. This signal then will be converted by the A/D-converter implemented inside the CPU with a resolution of 10Bits. This AD8310 chip is used to compress the signal from the detector diode, so a simple (low resolution) A/D-converter can be used.

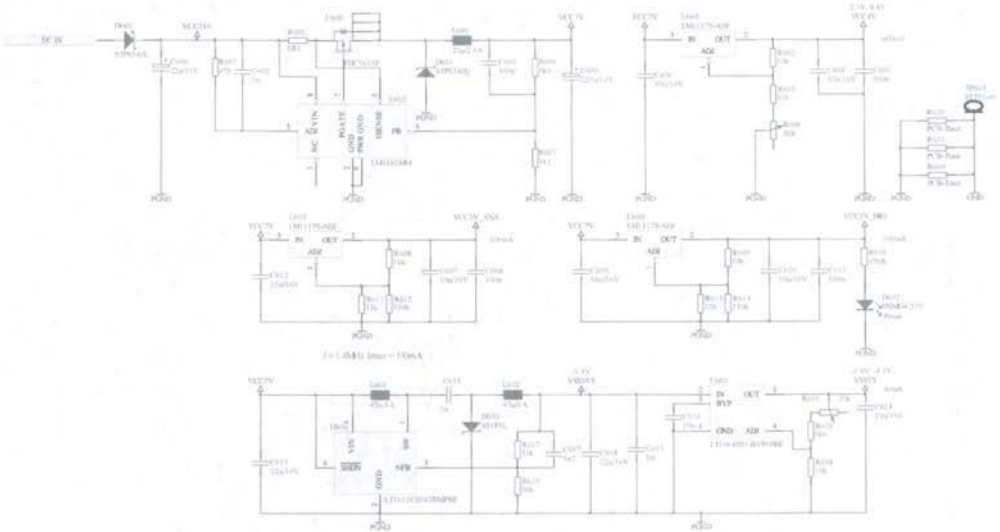


Figure 8F: Schematic of the CPU part (page 6)

The last page of the circuit diagram (Figure 8F) is dedicated to the power supply. The input voltage from the DC connector (range: +12V – +24V) is reduced by a switching regulator to about +7V. To avoid disturbing the sensitive analogue circuits by switching noise, all operating voltages are derived from this +7V rail with linear regulators. The reason for creating this 'intermediate voltage' rail is to lower the power dissipation, which in turn reduces the warm-up drift of the DC signals. The power consumption of the whole system is about 15W, so good cooling is necessary. The adjustable output voltage created from U601 is used for driving the AMMP-5024 amplifiers; R606 adjusts the bias point. U603 and U604 create a +5V supply for the analogue and digital components. U606 and U605 are used to create an adjustable negative voltage which is also used for the bias point of the AMMP-5024. This voltage also controls the (less sensitive) mixer bias voltage. The completed CUP and Power Supply board is shown in Figure 9.

3. Synthesizer

Because of the size of the circuits the Synthesizer PCB and also the adjustment will be presented in the next part of this article.

Software

The software running on the Atmel CPU emulates a serial interface via USB which is visible as a 'Virtual COM Port' on a connected PC. With the exception of a description file (*.inf file, see references) no drivers are necessary for a Windows PC. All the functions of the VNA can be tested with a simple terminal program (e.g. HyperTerminal, Figure 10). For a correct setup of the communication this program only needs to know the correct COM-port (visible in Windows Control Panel). Baud rate and handshake mode are not used and can be left on their standard values.

The control software, myVNA from G8KBB, was developed for the original N2PK VNA and uses a library called VnaDll.dll to communicate with that specific hardware. For use with this microwave VNA, the original version of VnaDll.dll (which was copied to the program directory by the myVNA installation program) must be replaced with a new version (see references). Then all functions of G8KBB's myVNA software can be used with this microwave VNA, for example as shown in Figures 1, 3 and 11 (except for I/O-Line debugging and 12-Term calibration).

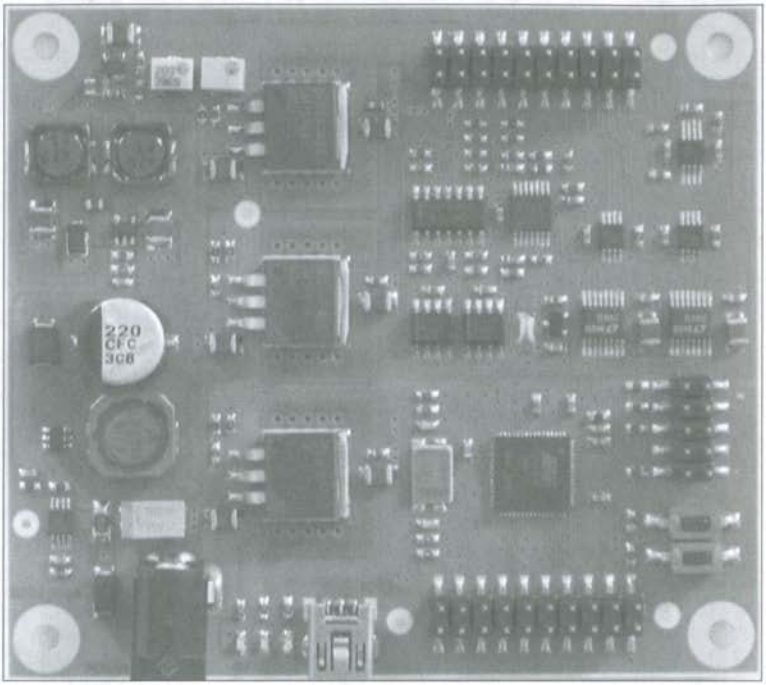


Figure 9: The assembled CPU and Power Supply board. On the left side is the power supply, at the bottom right the CPU and on the upper right the analogue part with two 24Bit A/D-converters. The two 20-pin headers connect to the Microwave board (top) and the Synthesizer board (bottom).

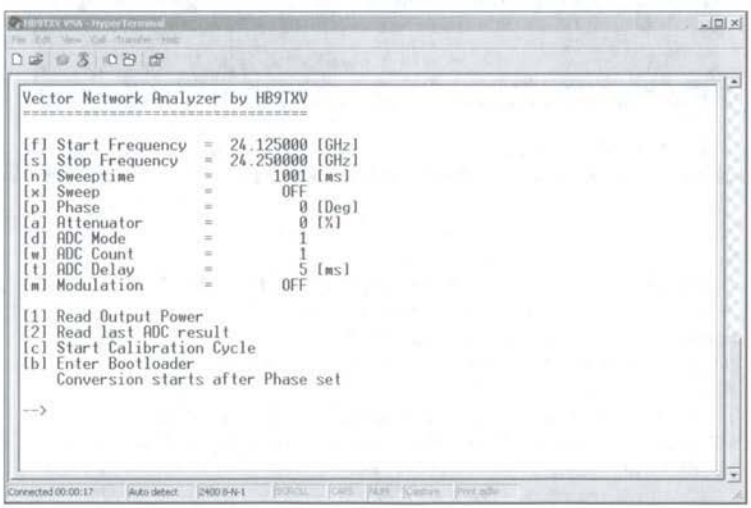

Vector Network Analyzer by HB9TXV
[f] Start Frequency = 24.125000 [GHz]
[s] Stop Frequency = 24.250000 [GHz]
[n] Sweeptime = 1001 [ms]
[x] Sweep = OFF
[p] Phase = 0 [Deg]
[a] Attenuator = 0 [%]
[d] ADC Mode = 1
[w] ADC Count = 1
[t] ADC Delay = 5 [ms]
[m] Modulation = OFF
[1] Read Output Power
[2] Read last ADC result
[c] Start Calibration Cycle
[b] Enter Bootloader
Conversion starts after Phase set
-->

Figure 10: The PC communicates with the VNA CPU via a 'Virtual COM Port'. For the first tests a terminal program as HyperTerminal can be used for communication. All parameters then are visible as plain text.

Overview

This first part of the article described the architecture of a do-it-yourself microwave VNA as well as the first two circuit boards. The second part will include the circuit description of the Synthesizer board as well as the implementation of the system. Some comparative measurements with professional systems will also be presented. All schematics, layout data and necessary software modules can be downloaded from the author's website after the publication of the entire article.

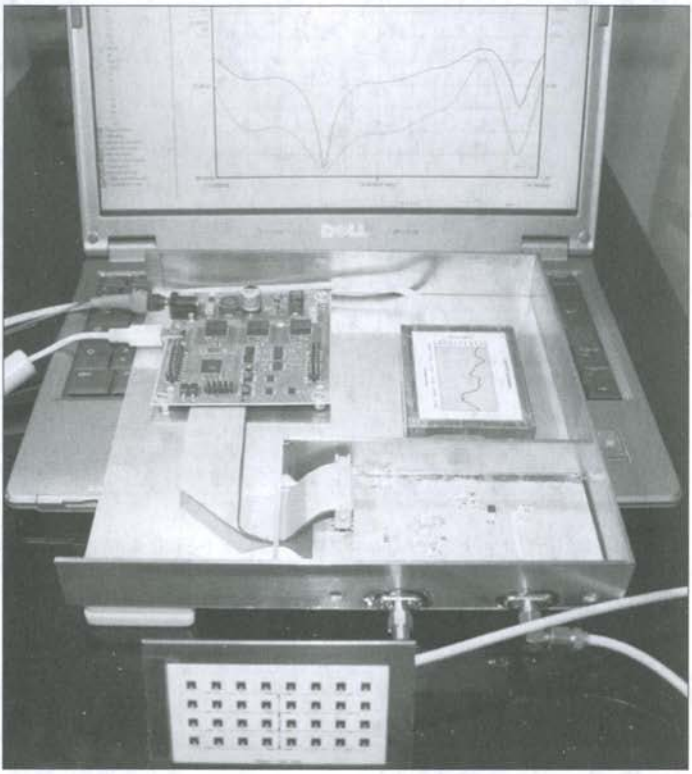


Figure 11: HB9TXV's Microwave VNA in use. Here a 32-element patch antenna with a resonance frequency of 23.850GHz (in front of the picture) is being measured.

References

Application Note 1287 from HP: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/HP-AppNote1287.pdf*
Agilent, Network Analyzer Basics: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/5965-7917E.pdf*
Software description, myVNA' (myVNA Quick Start Guide)
http://g8kbb.roberts-family-home.co.uk/myVNA_Quick_Start_Guide.pdf
Description of N2PK's VNA: *http://www.n2pk.com*
Datasheet AD8302: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/AD8302.pdf*
Datasheet AMMP-5024: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/AMMP5024.pdf*
Datasheet AMMP-6530: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/AMMP6530.pdf*
Datasheet HMC712: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/HMC712.pdf*
Datasheet MA4E2502: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/MA4E2502.pdf*
Schematic CPU part: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/Schematic_CPU.pdf*
Windows-Software for this VNA (*.inf and DLL):
http://www.rfbeam.ch/HB9TXV/Microwave_VNA/Software.zip

VNA for 5 – 30GHz (Part 2)

by Léon Audergon, HB9TXV - audergon@rfbeam.ch

This second part of the article describes the signal source of the Vector Network Analyzer (VNA), the commissioning of the system, the configuration of the PC software and some comparative measurements with a professional system. Since all measurements with a VNA are fundamentally a comparison of the device under test (DUT) with a well known reference, these references (Calibration Kits) are also described in more detail.

Circuit descriptions

The signal source of the VNA is built on a very similar approach to the synthesizer described in DUBUS 2/2009. A DDS generates a finely adjustable frequency in the range of 10–22MHz from a reference source (internal or external). This signal is converted into the 5–11GHz range by the use of a PLL. Two frequency-doublers finally create the two bands 10–22GHz and 22–30GHz. Selected by a matrix of switches, the signal frequency reaches the output jack (Figure 1).

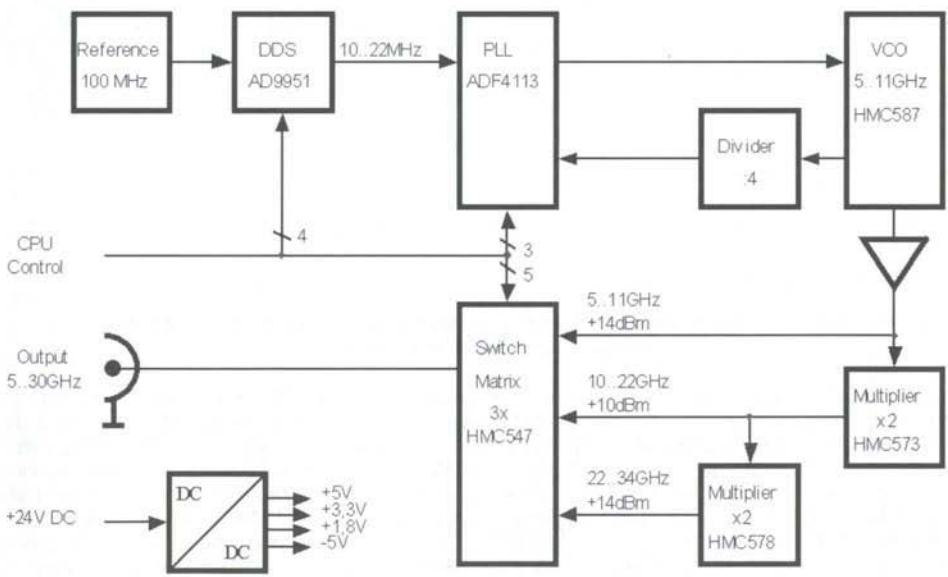


Figure 1: The broadband output of 5–30GHz is generated from a MMIC VCO with subsequent two stage doubling.

In this module I have used MMICs in many places, and these significantly simplify the construction of such a broadband circuit. Anyone who has already built a GHz oscillator with a tuning range of >2:1 with discrete components, will certainly agree with me.

The schematic of the synthesizer is divided into 5 pages, Figure 2a–e. As in Part 1, these schematics have been strongly reduced to save space, but can be downloaded as PDF file (see references).

The control signals from the CPU board reach the synthesizer over a 20-pin connector (X101 in Figure 2a). The 24V power can also be supplied via this cable, or if this assembly is to be used for other purposes, can be connected via the socket X103. X100 can be used to feed an external reference signal

(e.g. GPS-locked); otherwise the internal 100MHz crystal oscillator will be used. The generated microwave signal can be found on X102. This jack is a 2.92mm connector, which is mounted on a brass profile. More information on this connection can be found e.g. in DUBUS 4/2009, Figure 2a.

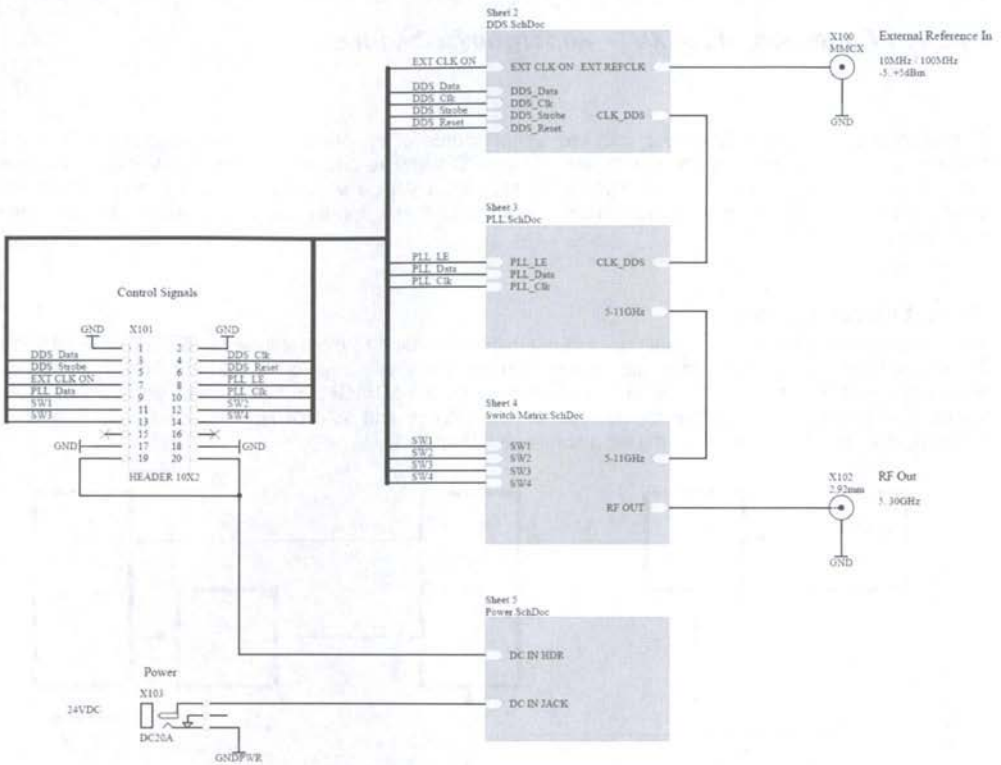


Figure 2a: Overview diagram of the synthesizer. The function blocks from Figure 1 can also be found in this diagram.

Figure 2b shows the generation of the reference frequency for the PLL with a DDS (Direct Digital Synthesizer). This technique provides a digitally tuneable frequency with very small increment steps. The signal delivered by U200 (AD9951 from Analog Devices) has a frequency range of 10–22MHz and can be set with a resolution of 0.1Hz. Before amplification with U201, the signal is freed from unwanted spurious with an LC bandpass filter. The reference frequency for the DDS is created from a low noise integrated oscillator U202 from Crystek. The frequency of this oscillator is fixed at 100MHz. An external reference (10MHz or 100MHz) can also be supplied via U203. This signal determines decisively the phase noise of the generated RF signal after (effectively) having been multiplied up to 5–30GHz and should therefore be of very good quality. A frequency of 100MHz is preferable, because in this case the internal PLL of the AD9951 (which creates a relatively high phase noise) is bypassed. Theoretically the synthesizer can work with any reference frequency up to about 200MHz if the software in the CPU board is adjusted accordingly (change of a constant).

Moving on to Figure 2c, the DDS signal serves as a reference for an ADF4113 PLL chip from Analog Devices (U300). It is internally divided by 5 and compared with the frequency of the VCO, which is divided by 2500 (division by 4 in the external component uPB1513 from NEC, then a further division by 625 in the PLL chip itself). Thus, the VCO oscillates at a frequency 500 times higher than the supplied reference signal. The range of the created signal is therefore about 5–11GHz. The oscillator itself is a HMC587 from Hittite. The control voltage (pin 4) is in the range of 0–18V so we need a DC amplifier between the PLL chip and the VCO (U301). The resulting RF signal is amplified by U304 (NBB-310, a 50Ω gain block from RFMD) and can be picked up after R310 at approximately +13dBm.

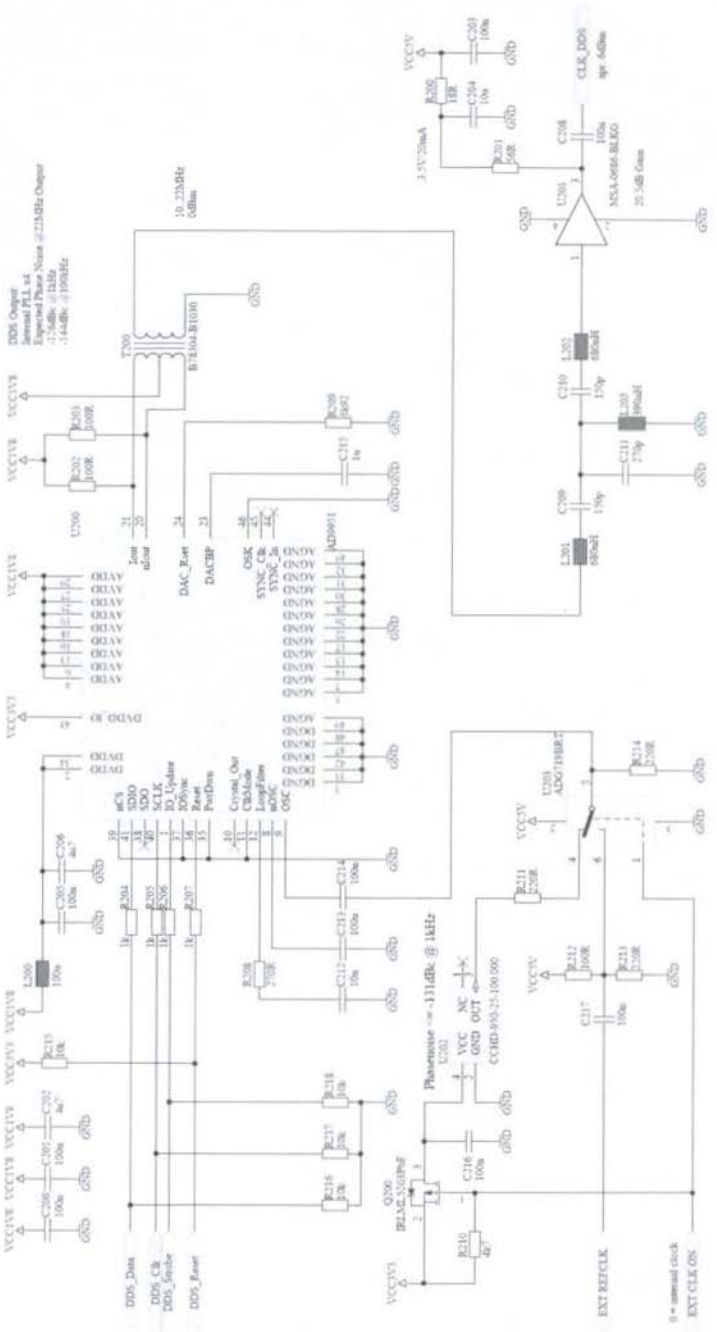


Figure 2b: A DDS (U200) generates a frequency in the range 10–22 MHz. This signal is multiplied by a PLL with a fixed factor of 500. The exact frequency can be programmed via the SPI interface of the DDS-chip.

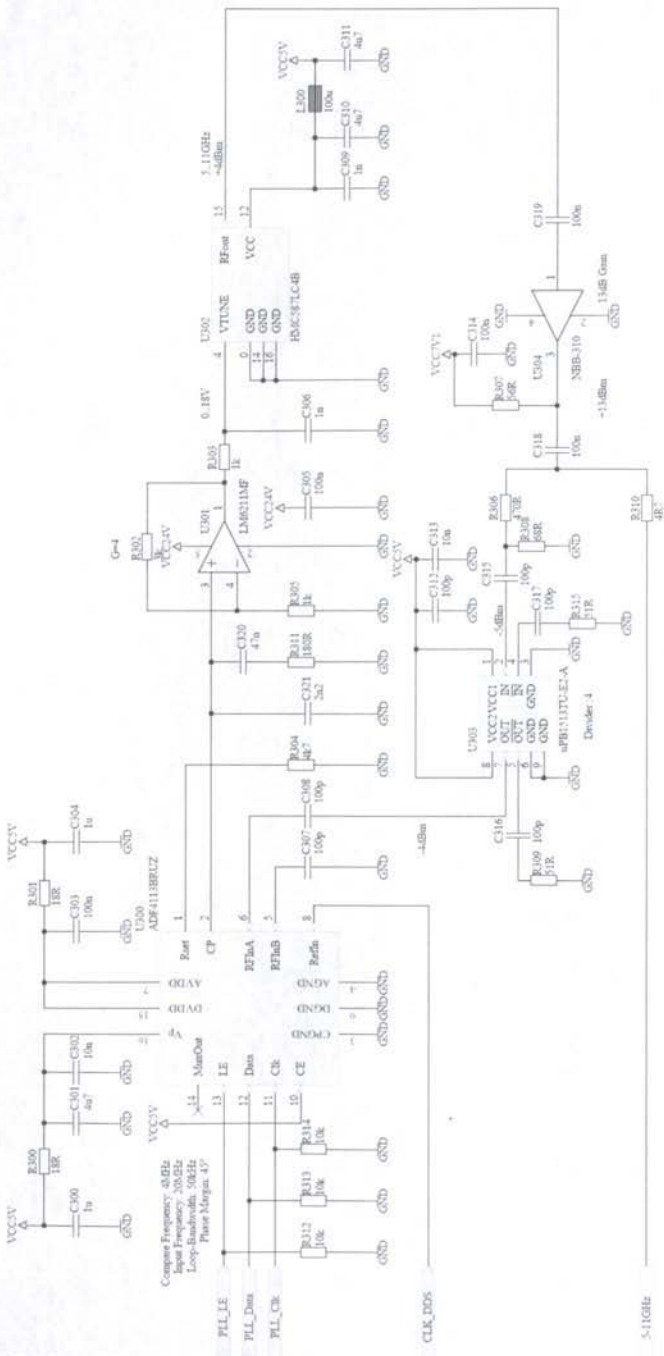
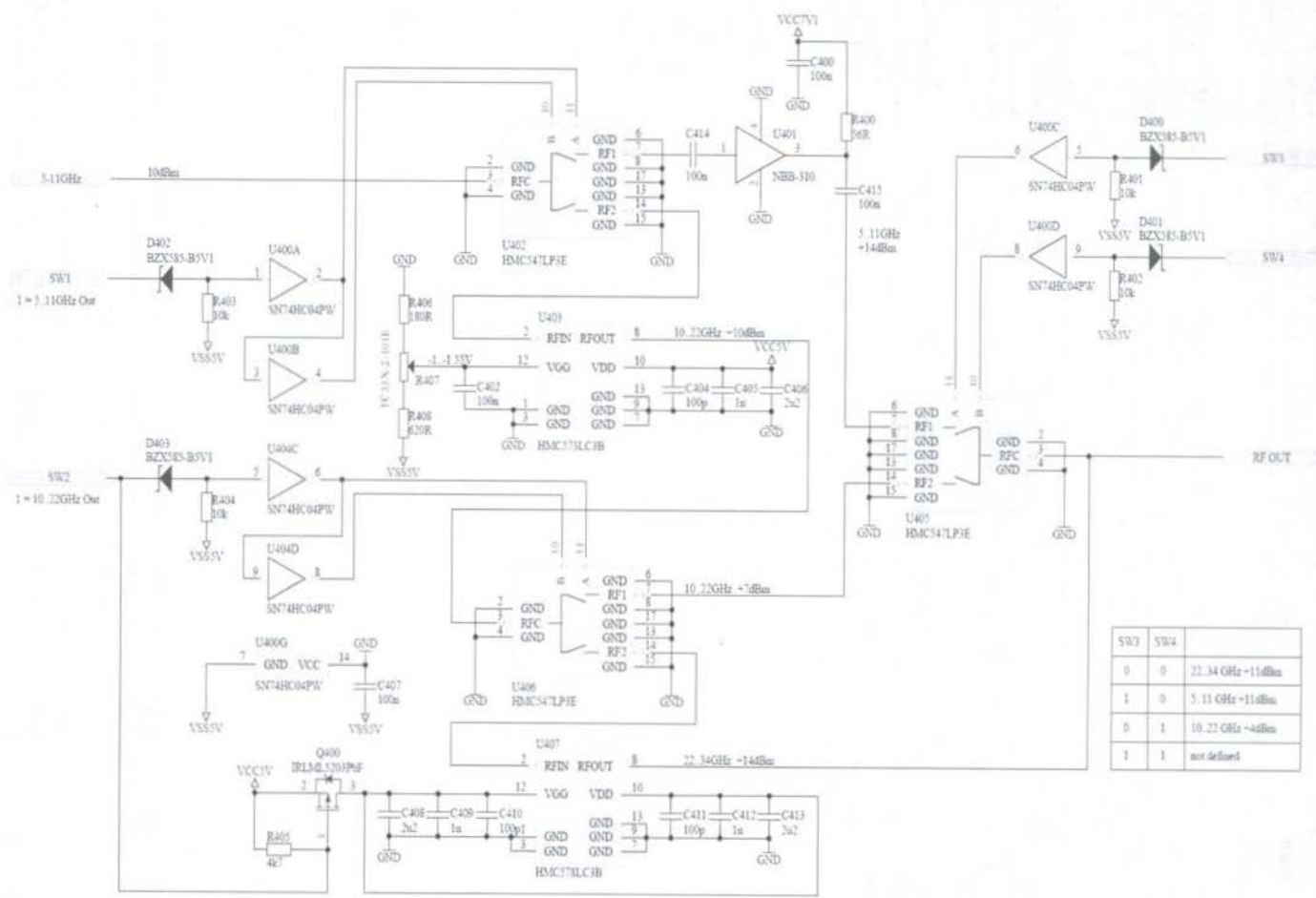


Figure 2c: U300 is the PLL which multiplies the reference frequency by 500. The output signal is amplified (U304) and then further processed after R310, in Figure 2d.



SW3	SW4	
0	0	22..34 GHz +14dBm
1	0	5..11 GHz +10dBm
0	1	10..22 GHz +7dBm
1	1	not defined

Figure 2d: By the use of several switches (U402, U405 and U406) and doublers (U403 and U407) we create two extra bands 10–22GHz and 22–34GHz and route them to the output.

In Figure 2d, the 5–11GHz ('Band 1') signal from U304 is now routed through the switch U402 (HMC547 from Hittite), another amplifier stage (U401) and a further switch U405 to the RF_OUT connector. This port is accomplished as a 2.92mm jack. On the PC board the microstrip trace ends at the edge where the RF_OUT connector is soldered on.

For higher frequencies, the 5–11GHz signal is routed via switch U402 to the doubler U403 (HMC573 from Hittite). This active doubler with an integrated filter provides at its output a signal in the range 10–22GHz ('Band 2') and a power of +10dBm. R407 is used to set the optimum operating point for U403, and has to be adjusted for maximum output power of the doubled signal. The resulting 'Band 2' signal is routed to the output via the switches U406 and U405.

Alternatively, U406 can switch this 10–22GHz signal to a further active doubler (U407, HMC578 from Hittite) to generate the frequency range of 22–34GHz ('Band 3') with an output power of +14dBm. Since this signal can be switched only with a large insertion loss, this Band 3 output was routed directly to the 2.92mm jack. The doubler is turned off via the power supply of U407 – a not entirely conventional way, but still functional.

Figure 2e finally shows the power supply of the synthesizer. The input voltage is either received from the connector X101 (connection to the CPU) or from X103. The input voltage of 24V is first lowered to a voltage of 7.1V by a step-down converter (LM3485 from National, U505). This is necessary in order to reduce the power dissipation of the linear regulators (+5 V, +3.3 V, +1.8 V). A voltage inverter (LT1611 from Linear, U504) generates a –5V supply, which is used for the RF switches and the frequency doubler.

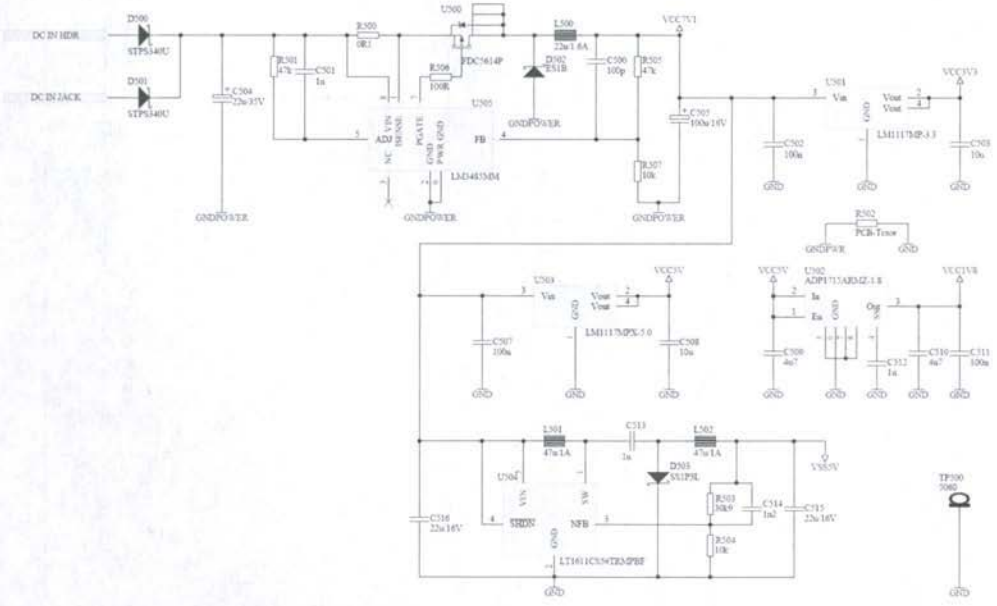


Figure 2e: The power supply of the synthesizer. To reduce the power dissipation a switching regulator followed by linear regulators is used. The power consumption is approximately 4 watts for a fully assembled PCB.

Thanks to the extensive use of MMICs the whole circuit can be constructed on a 4-layer printed circuit board with dimensions of only 60x94mm as shown in Figure 3. The board is mounted in a housing made of brass profiles. Connectors to the outside are: RF-output (2.92mm jack), the reference input (MMCX), the power supply (round connector) and a 20-pin ribbon cable. The use of many MMICs also makes it easier to reproduce this circuit (only 1 adjustment point). The disadvantages are that some of the MMICs are difficult for amateurs to obtain.

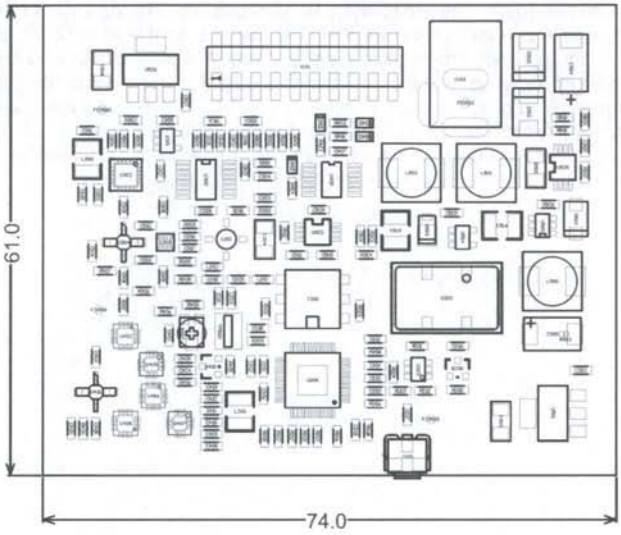


Figure 3: The layout of the synthesizer module.

Initial Startup Procedure

First, the CPU board described in Part 1 should be powered with 24V via the connector X4. Neither the synthesizer nor the microwave board should yet be connected. The current consumption is approx 40mA. Now you can program the flash memory of the CPU with the JTAG connector X200 (for this task you need a programming adaptor from Atmel). After an off/on cycle of the power supply the '5V' LED must be on, and the LED 'SL2' must blink 3 times and then remain switched on. Afterwards a Windows PC (Windows XP or higher) can be attached on the USB port. When the PC detects the USB device, the LED 'SL1' will light up. The PC should recognize a new hardware and ask for a driver file. After installing the appropriate *.inf file, the PC has an additional serial port available. In the Device Manager (Control Panel) the port number of this new connection can be determined (Figure 4):

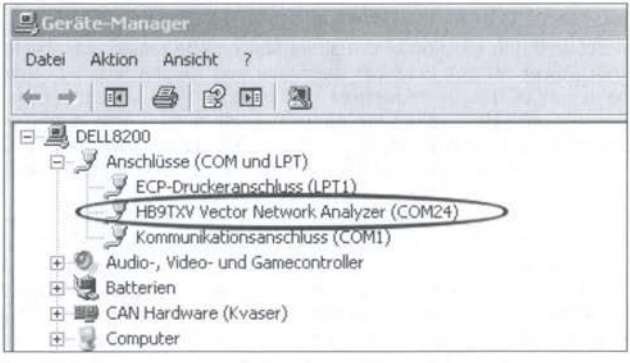


Figure 4: The Vector Network Analyzer is visible to the PC as an additional serial interface. In this case, that would be port COM24. This setting must be entered in the configuration file vnadll.cfg so the software can communicate with the CPU board.

A terminal program (e.g. HyperTerminal) can now establish a connection to the VNA. For this hardware we need only to declare the correct port number (in the illustrated example COM24). All the remaining parameters such as baudrate or handshake method are not relevant for us and can remain unchanged. After pressing the <ENTER> key, the VNA sends a menu to the screen. An illustration can be found in the first part of this article, Figure 10.

With the two potentiometer R606 and R615 the two voltages VCC4V and VSS3V can be adjusted to +4.0V and –3.0V respectively. If everything went well so far, the synthesizer board can be connected to X3 on the CPU board with a 20-pin ribbon cable. The length of this cable is not very critical, but should not exceed 200mm. It should now be possible to set the output frequency of the synthesizer with the command 'Start Frequency' (e.g. to produce a frequency of 12.735GHz you have to enter 'f12.735'). By the use of the commands 'Stop Frequency', 'Sweeptime' and 'Sweep' you can also produce frequency sweeps, which can be monitored on a spectrum analyzer. There must be no 'holes' in the whole range and the power should stay within the range of +2dBm to +14dBm (Figure 5).

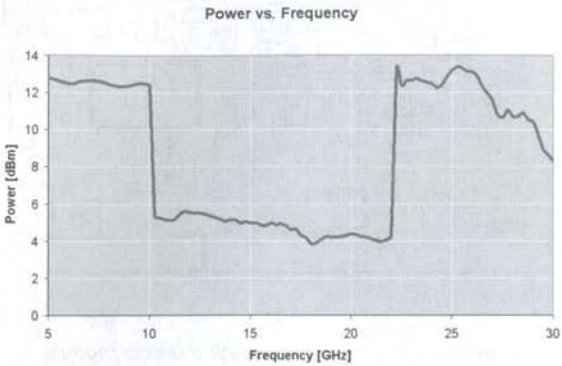


Figure 5: This picture shows the output power versus frequency for the prototype of this synthesizer. The power 'jumps' at 10GHz and 22GHz are caused by the band switching.

With the potentiometer R407 on the synthesizer module, the output power of Band 2 (10 ... 22GHz) can be maximized. Now also the microwave board can be connected to X2 of the CPU board. The RF output of the synthesizer is connected to the RF input of the microwave part (X3). This should be done with a low-loss cable that is suitable for this frequency range (e.g. semi-rigid cable). A frequency sweep produced by the synthesizer should now be visible at the S11 port of the VNA. If the microwave part self-oscillates (even without a connected synthesizer), this can often be avoided when the AMMP-5024 chips are covered with absorber (pieces with a size of 10x10mm are enough, I use for this purpose Eccosorb GDS material). If this does not help, the inputs of the AMMP-5024 could be grounded by 100Ω resistors (size 0402 or smaller). This must be done as close as possible to the amplifier.

If everything worked out well, the function of the attenuator can be tested with the terminal command 'a' (Figure 6). The output power on port S11 can be measured roughly via a directional coupler on the microwave part. The result of this measurement can be displayed with the command 'Read Output Power'. The display is a single HEX-value; the larger the value, the more output-power we have. This measurement is not (yet) used by the Windows software. The output power at the S11 port should stay within about –5dBm to +5dBm depending on the chosen frequency (as measured with a power meter with the attenuator set to 0.

Now the S11 and S21 ports of VNA can be connected by a short cable. The command 'm' (modulation) starts the generation of a signal with a frequency of approximately 3Hz which controls the vector modulator U4 on the microwave board. This causes a continually changing phase of the LO-signal. On the output of mixer U5 (across R7) we should now be able to measure a sine voltage of a few mV.

When we remove the connection between the S11 and S21 ports, this signal should disappear (or at least become much smaller). If nothing is connected at port S11 (equivalent to a poor return loss, since the entire RF power is reflected) we must now be able to measure a sine signal on the output of mixer U6 (across R10).´ If no problems occurred up to now, the S11 and S21 ports can be connected again. The command 'c' (calibration) can now be started. This command calibrates the vector modulator and it takes several seconds to complete. The frequency is automatically swept from 5GHz to 30GHz in 100MHz steps. For each frequency two phases are searched for, which have a difference of exactly 90°. These values then are stored in the non volatile memory of the CPU board. Thus the modulator phase error can be minimized.

Thus, the first commissioning of the hardware is completed. All other functions are tested with the 'final' PC software myVNA from G8KBB (see references). I am aware that these instructions are kept very short, due to the complexity of the device, and in case of problems I will try to help individually.

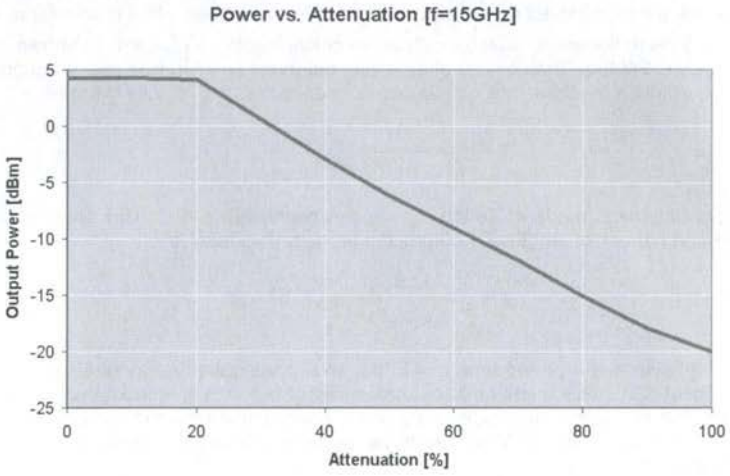


Figure 6: For this measurement the attenuator on the microwave board was operated. The output frequency from the synthesizer was permanently set to 15GHz, and the attenuation was swept from 0% to 100%.

PC-Software 'myVNA'

Now the PC software from G8KBB can be installed. Since this program was originally written for different hardware (the original N2PK VNA) it cannot work directly with the hardware presented here. In the installation directory (usually `C:\Program Files\G8KBB\myVNA`) we have to replace G8KBB's original file called `vnadll.dll` with a version specially customized for this VNA, and have to add another file `vnadll.cfg`. Then the software can be started. On the left side of the display is a 'tree view' in which the following parameters must be set:

Instrument Mode	Reflection
Display Left	RL
Display Right	<Rho
Calibration	6 Term Calibration
Reference Standards	C_{op}=0, R_{sh}=0, L_{sh}=0, R_{ld}=50, L_{ld}=0, C_{ld}=0
VNA Hardware	
Transmission uses	ADC2
Reflection uses	ADC1
ADC Step Delay	0
Sweep Start Delay	0
Phase Change Delay	0
ADC Speed	1
Clock	100MHz
Maximum Frequency	30MHz
Minimum Frequency	5MHz
Hardware Interface	USB
CDS/Harmonic Mode	Harmonic Suppression Mode, 4 Samples
Switch and Attenuators	Attenuator 0

Installation details and relevance of the parameters set here can be found in the excellent manual by Dave, G8KBB (see references). Now, our system is ready for the first measurement... except for the question of the Calibration Kit.

Calibration Kits

A VNA always makes a comparative measurement of the connected DUT (Device Under Test), relative to measurements already made using a set of known calibration standards. This is necessary, since even the smallest changes on the test setup such as inserting an additional coaxial adapter or a small piece of

cable will have a significant impact on the amplitude or phase response. Here is an example:

We consider an SMA male/female adapter with an electrical length of 12.6mm, as shown in Figure 7. The working frequency is 24GHz. The velocity of an electromagnetic wave in free space equals to c_o, which is about $3x10^8$m/s. Within a medium, including inside our connector, the velocity is lower:

$$v = \frac{1}{\sqrt{\mu_0 \cdot \mu_r \cdot \varepsilon_0 \cdot \varepsilon_r}}$$

If the insulation material is made of Teflon, so we can count with ε_r=2.2. This gives a velocity of about $2.02x10^8$m/s. For a connector length of 12.6mm, the propagation delay is:

$$t = \frac{l}{v} = \frac{12.6 \cdot 10^{-3} m}{2.02 \cdot 10^8 \frac{m}{s}} \approx 62.4\ ps$$

A frequency of 24GHz has a period time of 41.7ps, so a propagation delay of 62.4ps corresponds to a phase shift of about 538°. This means that our measured phase with or without this 'small' adapter differs by this amount! The measured amplitude can also have significant errors in the range of several dB due to mismatches. For this reason, a VNA has to be calibrated before the measurement with exactly the setup that will be used.

If our DUT has a male 2.92mm plug, the female 2.92mm connector of our VNA must be calibrated with a male Calibration Kit with an electrical length of 0°. This means that the used calibration standards (Open, Short, Load) must all have their 'characteristic' open-circuit, short-circuit or termination at exactly the same position which then becomes the 'reference plane' for all subsequent measurements. Every small deviation during calibration will lead to significant errors in the later measurements.

As a calibration directly at the desired reference plane is often not feasible due to manufacturing reasons, Calibration Kits for the GHz range often have well-defined electrical lengths. On a 'short' for example, this length defines the exact distance from the reference plane of the connector to the physical short itself. This distance will almost certainly be different between the 'short', the 'open' and the 'load' standards, so the VNA firmware includes the individually declared lengths in its calculation. When measuring with a VNA one may also use a cable between the VNA and the DUT, but then one must perform the calibration at the 'working' end of the cable – effectively, the cable is then included as part of the calibrated measuring instrument. However, the measurement uncertainty becomes larger with increasing cable length, especially at microwaves, so it is recommended to measure as close as possible to the VNA.
The 'myVNA' software used here was originally designed for use up to only 60MHz so it does not (yet) support the inclusion of different electrical lengths of calibration standards. Thus, our standards must all have exactly the same length. After the calibration the measurement port of the VNA has to be extended by exactly the same amount. Professional VNAs also have a so-called 'de-embedding' function which allows a subsequent compensation for an inserted cable. If such a de-embedding should be necessary with the presented system, this has to be done externally by exporting the S-parameters and doing the calculation with e.g. an Excel spreadsheet.

This brief essay probably explains why a purchased Calibration Kit for the GHz frequency range must be very expensive. A good coaxial Calibration Kit specified for frequencies up to 40GHz costs around 10,000€! When buying second-hand kits (e.g. from eBay) one should pay attention that this kit is in a perfect condition. For example, if the kit is incomplete or even minor mechanical wear or damage is visible, it is absolutely inadvisable to purchase it.

What we need are not necessarily perfect calibration standards, but only **well-characterized** standards that are **stable over time**. These standards can be characterized on a previously calibrated microwave VNA, and can then be used for our purposes. This raises the question of which data from our personal Calibration Kit must be measured.

Open

We anticipate that our VNA has a female test port connector. Let us consider what happens when a SMA male/female adapter from Radiall (Model 125.704.000) is used as an 'open' standard. This adapter was chosen because it has a good price/performance ratio. Although it is only specified up to 18GHz, it can be used up to 25GHz. If this is not enough, the choice should fall on a 2.92mm adapter. If this male/female adapter is mounted on the S11 port, we have extended the reference plane by 12.6mm (value taken from the data sheet). A simulation should show us exactly what happens at the end of the connector.

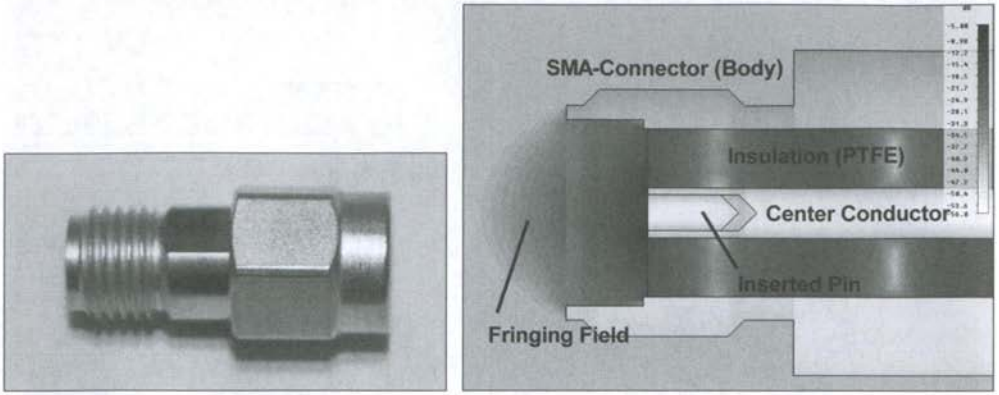


Figure 7: On the left, the Radiall SMA adapter used as an 'open circuit' standard. The male end is connected to the VNA; the female end is left open. The 24GHz simulation on the right shows the standing wave along the internal transmission line and the E-field at the open end.

The simulation in Figure 7 shows, as expected, a standing wave in the dielectric of the adapter. At the open end a small fraction of the energy is radiated (fringing field). For this simulation we inserted a pin into the centre conductor of the adapter. This pin ends exactly at the same position as the dielectric. This helps us to keep the impedance of the connector at 50Ω up to the reference plane. By the use of the simulator we then calculated the exact electrical length of this adapter. We got a value of 13.07mm. If this length is inserted in the calculation, the amplitude and phase response of the open connector can be determined (Figure 8).
If we use this adapter as an 'open' with an electrical length of 13.07mm, the maximum phase-error would be within +/-5° and the amplitude-error would be within +/-0.15dB. These are certainly not fantastic values, but are already sufficient for many cases. If we use the correct length of the adapter (12.6mm) so we can calculate the parasitic fringing capacitance for all frequencies. We obtain values, which can be entered in myVNA as correction values. The thus achieved (theoretical) accuracy will be +/-1° and +/-0.1dB in a bandwidth of 1GHz. To ensure we achieve this accuracy in practice, these capacitance values should be measured on a calibrated system. Measurements from the author showed, that the measured values are in good agreement with the simulated ones.

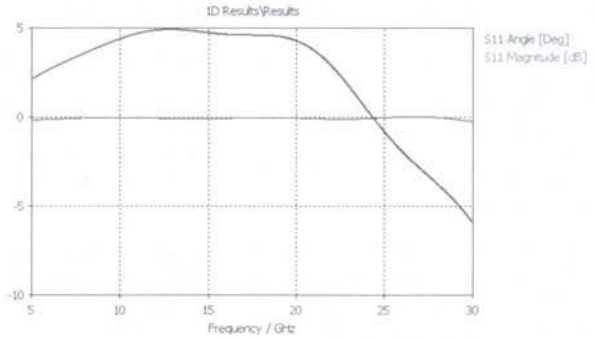


Figure 8: The resulting amplitude and phase errors when the above adapter is used as a 'perfect' open standard with an electrical length of 13.07mm. The phase error can be further minimized by using the calculated capacitance as a correction value in the software. Caution: These are simulated values, not measured ones!

Short

Also a 'perfect' short-circuit can be simulated easily. The already used adapter from Radiall is completed by a male SMA short cap. This consists of a gold-plated, round metal disc with a 'thorn' in the centre, which serves as a pin for the centre conductor of the adapter (Figure 9):

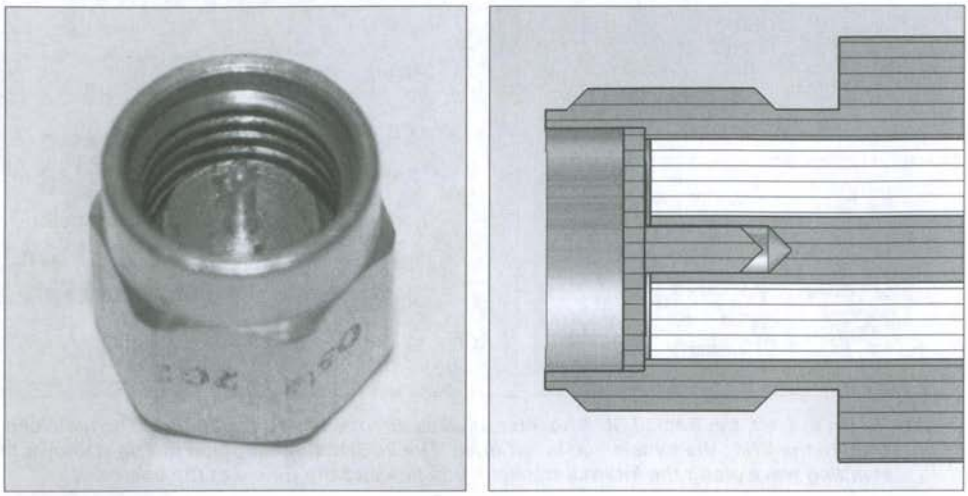


Figure 9: On the left, a standard SMA short. This is screwed onto the same Radiall adapter as Figure 7. On the right is the cross-section through the simulation setup (only the metal disc and the centre pin need to be modelled).

Here, the simulation provides a length of 12.88mm and a maximum deviation of ±4° in the phase, and ±0.1dB in amplitude. These values apply at a short inductance L_{sh}=0. Again, if we use the original length of the adapter and calculated values for the Inductance L_{sh}, we can increase the accuracy further (see next section). Also in this case a measured standard is always better than a simulated one!

Load

A perfect 50Ω-load is much harder to build than an open or short. For this reason, here we have no other choice than to obtain an as good as possible SMA 50Ω-load, and then to measure it on a calibrated system. If the accuracy requirements are not too high, we can also work with simulated-only results.

Summary

- The use of a port extension (Male/Female adapter) makes sense, so that the exact position of the reference (open, short or load) is moved as little as possible (by screwing or unscrewing the adapter). Also the influence of the test port connector at the VNA is minimized.
- An open reference can be built with an open-ended SMA Male/Female adapter and (frequency dependent) correction values.
- A short reference can be built with an SMA Male/Female adapter having mounted a short-circuit cap and (frequency dependent) correction values.
- A load reference is 'good' SMA termination screwed on a Male/Female adapter. This system should be measured on a calibrated VNA. At a pinch, one can also work with this adapter and inductance / capacitance values assumed from 'experience'.

Whenever possible, the home-made calibration standards should be measured on a calibrated VNA system. The determined values (capacity and inductance) can then be further processed in myVNA. In contrast to a 'real' professional Calibration Kit, our values are only valid for a limited frequency range. Professional standards have polynomial formulas for the entire specified range. Further information can be found in the application note 1287-11 from HP (see Appendix).

The 'Poor Man's Calibration Kit'

This section describes the construction (or rather, selection) of a low-cost male 3.5mm SMA Calibration Kit, which can be used up to approximately 25GHz. The parasitic capacitances and inductances can be measured in a calibrated system. If such a system is not available, one can also use the empirical values described here. In this case the measurement errors will be significantly larger and will depend on the assembly.

Open

We use the Male/Female Adapter from Radiall, article 125.704.000, already described above. On the female side, an SMA Open (SC2165 from Fairview Microwave) is attached. This consists of an open-circuit centre pin which terminates the centre conductor of the Radiall adapter at the reference plane, and a cap which 'terminates' the fringing field so that objects in the vicinity of the adapter do not disturb the measurement. Instead using an SMA open, one can also use a dust cap without a centre pin, although this leads to errors at frequencies above about 18GHz because a centre pin must be inserted to ensure a constant diameter over the whole length of the centre conductor.

Short

Again, the same Male/Female Adapter from Radiall is used, but on the female side of the adapter we attach an SMA Short cap (gold-plated, e.g. SC2135 from Fairview Microwave).

Load

To produce a normalized load we again use the Male/Female adapter from Radiall, and terminate it on the female side with a high-quality 2.92mm 50Ω termination. A 2.92mm termination is much more expensive than a 3.5mm model, but it also provides significantly better results in the range below 30GHz. I have used for this purpose the type ST4010 from Fairview Microwave.

Through

A 'Through Standard' is used to calibrate an S21 measurement (transmission). In most cases the DUT has female SMA connectors and is connected to the test ports of the VNA by two Male-Male jumper cables, so it makes sense to use as the standard a Female/Female SMA adapter of known length. I am using the adapter R125.705.001 from Radiall. The jumper cables must be of high quality with correctly attached Male connectors. A movement of these cables between the calibration and the measurement can lead to significant phase errors, so I use semi-rigid cables.

The three reflection standards – Short, Open and Load – each have an electrical length of 12.6mm and can be used up to about 25GHz. The frequency range can be extended upwards if we use 2.92mm adapters instead of the Radiall ones. The length of the through adapter (10.44mm) needs to be corrected after the measurement to obtain more accurate phase information. After performing an OSL calibration with the kit described here, we have to extend the test port with an identical Male/Female adapter. Otherwise the reference plane will lie 12.6mm too far 'behind'!

The following table lists the frequency-dependent, empirical correction values for C_{op}, R_{sh}, L_{sh}, R_{ld}, L_{ld} and C_{ld}. The values for the 50Ω termination are estimated values since they strongly depend on the individual type of termination resistor.

Frequency	Open	Short		Load		
	C_{op}	R_{sh}	L_{sh}	R_{ld}	L_{ld}	C_{ld}
5GHz	33.9fF	0Ω	19.5pH	50Ω	28pH	30fF
10GHz	33.6fF	0Ω	29.3pH	50Ω	28pH	30fF
15GHz	36.9fF	0Ω	33.4pH	50Ω	28pH	30fF
20GHz	40.3fF	0Ω	44.2pH	50Ω	28pH	30fF
25GHz	48.4fF	0Ω	50.9pH	50Ω	28pH	30fF
30GHz	55.2fF	0Ω	68.0pH	50Ω	28pH	30fF

Figure 10: The 'Poor Man's Calibration Kit'. From left to right we see Open, Short, Load and Through.

The first measurements

Before we can start the first measurement, we have to specify the frequency range. Since the 'myVNA' software knows nothing about our frequency generation and the multipliers, we have to scale all frequencies, capacitances and inductances. A programmed frequency range of 5.0MHz – 30.0MHz represents an output frequency of 5.0GHz – 30.0GHz. All capacitances and inductances of the Calibration Kit must be scaled by the same factor: a fringing capacitance C_{op} of 30.0fF has to be entered as 30.0pF, and so on; but for the first measurement we will keep the parasitic capacitances and inductances of the calibration standards at 0.

When we program a frequency range from 23.5–24.5GHz, we have to enter in myVNA the frequency range 23.5–24.5MHz. We want to make a reflection measurement, so we set the mode of operation to 'Reflection'. After following the instructions for OSL (Open, Short, Load) calibration, we start the measurement with display mode 'Smith-Chart'. The first measurements will be of the calibration standards themselves. These are connected in sequence to the S11 test port, and on the author's hardware the measurement looks the following (Figure 11):

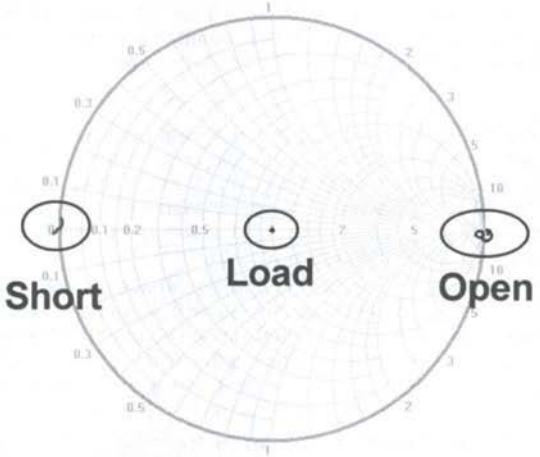


Figure 11: Measurement of open, short and load in the frequency range 23.5–24.5GHz, 30 minutes after calibration. To reproduce this measurement you need to set the parasitic effects of the Calibration Kit to 0.

Figure 12 shows on the left side the return loss (S11) of the Calibration Kit's 'Load' standard, 30 minutes after the calibration was first made. We are measuring here the combined effects of drift and reproducibility of connections, and it turns out that the effective dynamic range is about 38dB (at 24GHz – at lower frequencies, the dynamic range is larger). On the right side of Figure 12 is the S21 crosstalk; the result here is about –60dB, which implies a 60dB dynamic for measuring the losses of passive devices. It is also possible to measure gains of active devices, which will enhance the dynamic range accordingly. All of these measurements were made without averaging, in approximately 100 Hz bandwidth.

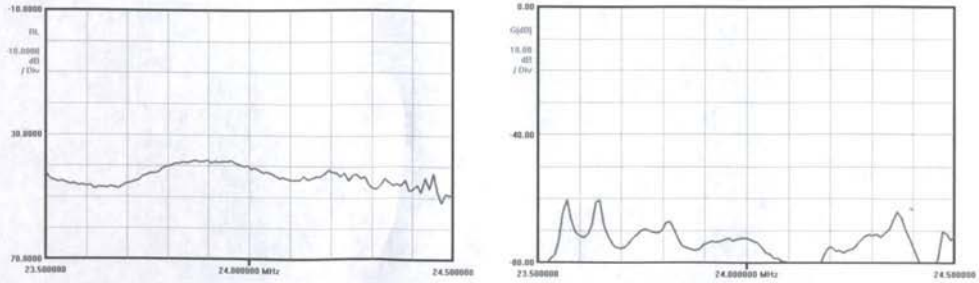


Figure 12: The dynamic range for reflection measurements in the 24GHz band is approximately 38dB (left). For S21 measurements up to 60dB loss can be measured (right).

Some comparative measurements have also been made against a professional microwave VNA. Figure 13 shows the measurement of a 12GHz patch antenna with an Anritsu 37269C VNA and our system. The Anritsu VNA was calibrated using its own Calibration Kit, while our own VNA was calibrated using the Poor Man's Calibration Kit. The absolute deviation is about 0.7dB (amplitude) and 6° (phase). It is noted that the influence of the cabling or improper tightened SMA connectors can cause errors of a similar magnitude.

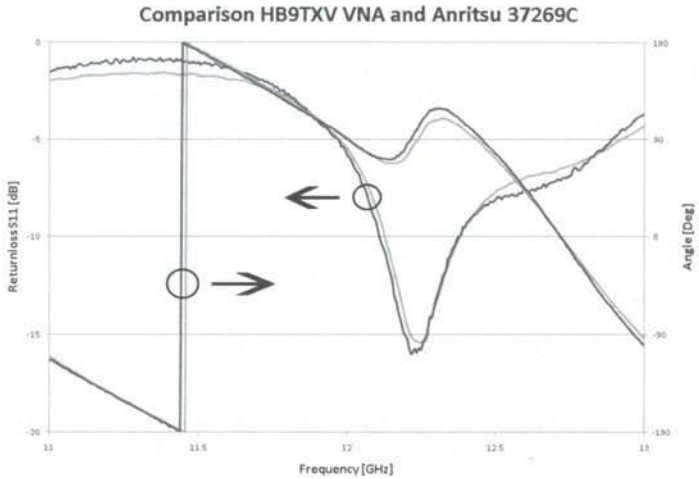


Figure 13: A 12GHz patch antenna was measured with a professional system (Anritsu 37269C, 40GHz VNA with corresponding Calibration Kit, grey line) and the system presented here (with Poor Man's Calibration Kit, black line).

Conclusion

This system shows that it is possible to build a microwave VNA with amateur equipment and a modest budget. The achieved dynamic ranges of about 40dB for reflection and about 70dB for transmission loss in passive systems are close to what can be reached with professional systems. Only the slower measurement speed of about 50–100ms per point is significantly lower than today's professional microwave VNAs.

Although this project is not suitable as an 'initial project' in the microwave world, I would appreciate reports from experienced amateurs building this or similar systems. Also suggestions, adjustments to other frequency bands, or extensions of the software are always welcome!

References

Application Note 1287-11 from Agilent Technologies (Specifying Calibration Standards):
http://www.rfbeam.ch/HB9TXV/Microwave_VNA/5989-4840EN.pdf
Datasheet AD9951 (DDS-Chip): *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/AD9951.pdf*
Datasheet HMC587 (VCO): *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/HMC587.pdf*
Datasheet HMC547 (Switch): *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/HMC547.pdf*
Datasheet HMC573 (Frequency Doubler): *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/HMC573.pdf*
Datasheet HMC578 (Frequency Doubler): *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/HMC578.pdf*
Schematic Synthesizer: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/Schematic_WB_Synth.pdf*
Datasheet Radiall Adapter 125.704.000:
http://www.rfbeam.ch/HB9TXV/Microwave_VNA/Radiall_125704000.pdf
Datasheet SMA Short SC2135: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/SC2135B.pdf*
Datasheet SMA Open SC2165: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/SC2165B.pdf*
Datasheet SMA Load ST4010: *http://www.rfbeam.ch/HB9TXV/Microwave_VNA/ST4010B.pdf*
Coaxial Cable Delay from VE2AZX: *www.rfbeam.ch/HB9TXV/Microwave_VNA/CoaxialCableDelay.pdf*